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Smart Sensor Network for Aircraft Corrosion Monitoring

2010 U.S. Army Corrosion Summit

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Outline

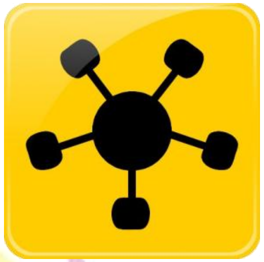
- Smart Sensor Network
  – *Needs and technology overview*
- Network Elements
  – *Hub, Network capable application processor (NCAP)*
  – *Node, Smart transducer interface module (STIM)*
- Corrosion Sensing and Measurements
  – *Corrosion rate*
  – *Cumulative corrosion*
  – *Environmental parameters*

Issue / Need

- Aircraft corrosion is a leading maintenance cost driver that impacts readiness and safety
  - *Costs increase as the fleet ages*
- A corrosion monitoring system for current and future weapon systems is need to:
  - *Identify, track and locate environmental conditions that cause corrosion damage*
  - *Improve inspection efficiency by identifying only those aircraft and systems that require attention*
  - *Reduce maintenance costs through early detection*
  - *Maximize operational availability*

Sensor Node and Hub

- Sensor Hub
  - *Centralized wired or wireless data hub provides communications between user network and sensor network*
  - *Embedded processing for on-board data reduction*
  - *Ultra-low power, for use with energy harvesting technologies*
  - *Open architecture*



- Sensor Nodes
  - *Distributed sensor nodes for corrosion hotspot monitoring*
  - *Wired or wireless interface to sensor hub*
  - *Flexible modular design can support a wide variety of sensors*
  - *Integrated sensor elements for corrosivity and corrosion measurements*
  - *IEEE-1451 compliant for plug-and-play simplicity*

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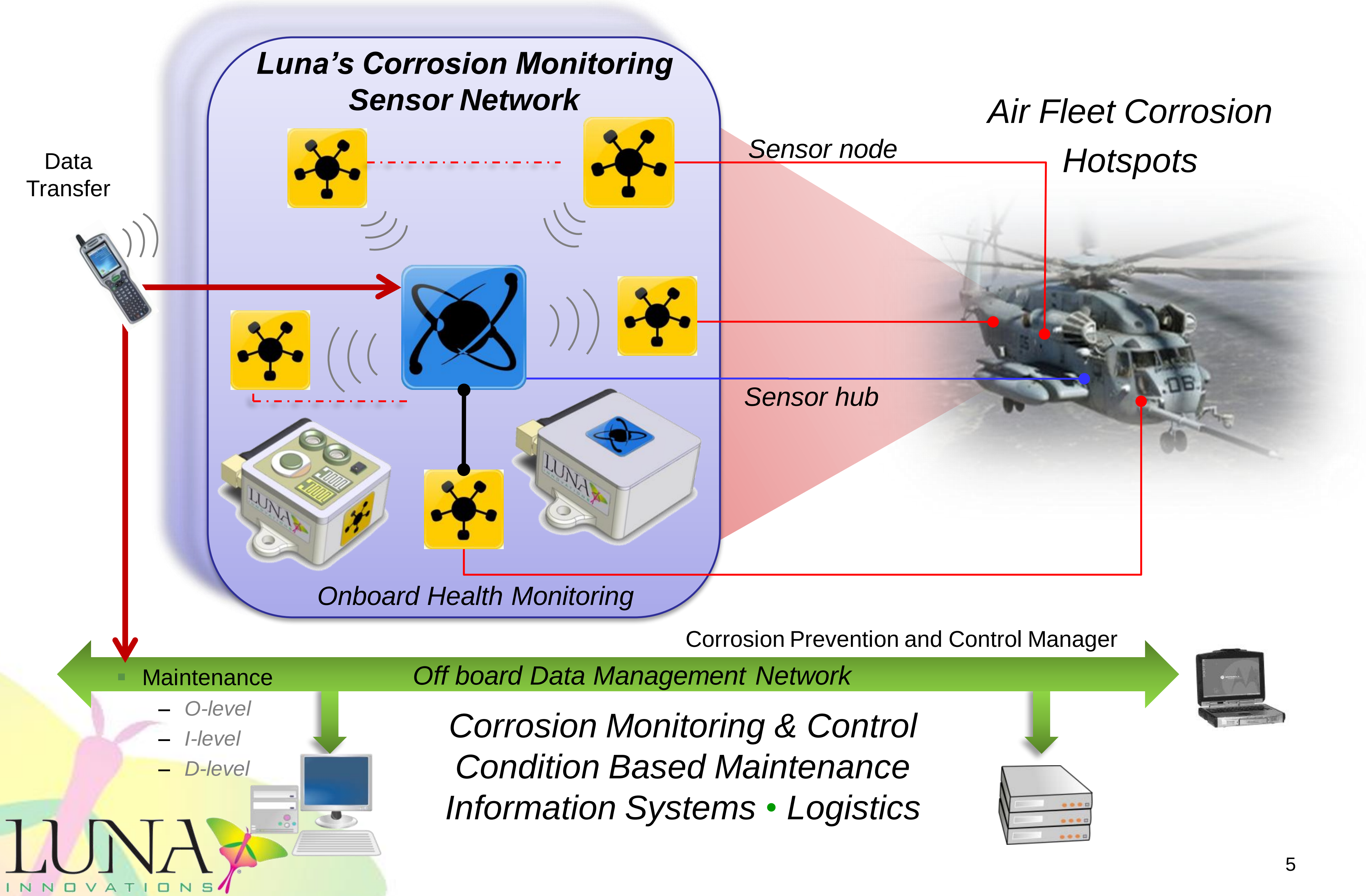
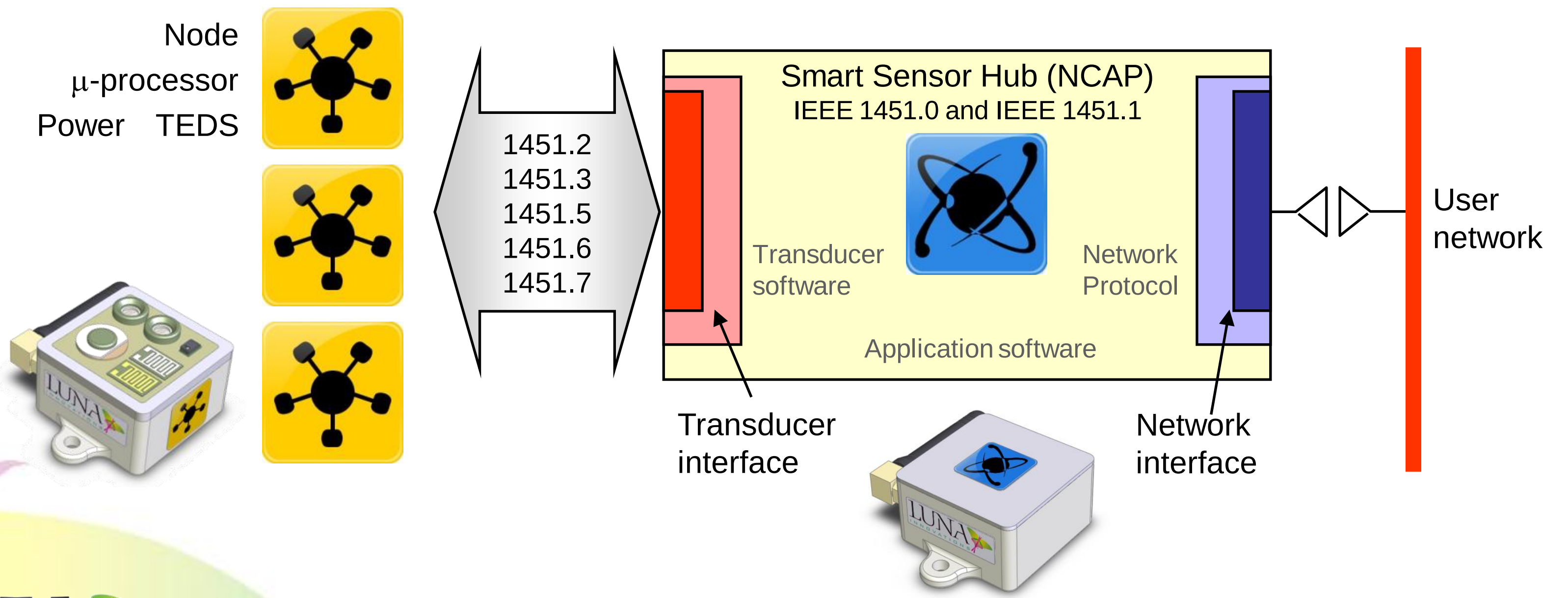
Vehicle Health Management



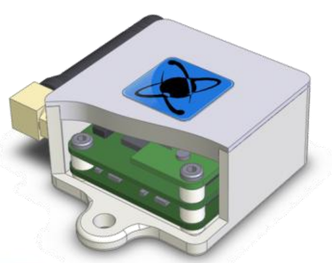
Sensor Node and Hub

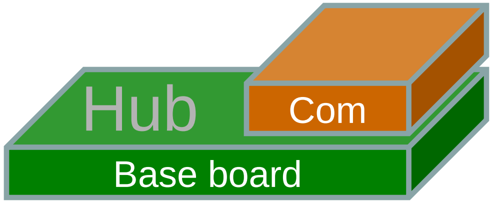
- IEEE-1451 standard defines sensor node and hub
  - *Both sensor node and hub are based off common hardware*
  - *Sensor hub interfaces with user network and sensor nodes*
    - Wired or wireless communications with other system elements
  - *Sensor node interfaces with transducer elements and hub*
    - Communications between hub and node can be wired or wireless
    - Node contains transducer electronic data sheets (TEDS)
      - Plug-and-play capabilities between sensor nodes and hub elements

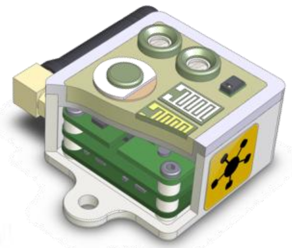


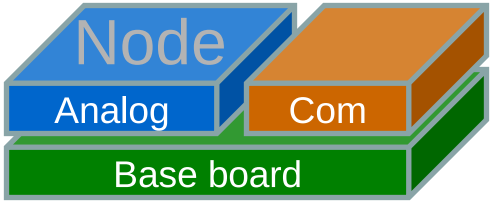
Modular Sensor Node and Hub

- Modular design allows for ease of development and application customization
- Design consists of three main hardware elements: base board, communications board, and analog board
  - *Base board is common to sensor node and hub*
    - microcontroller, power regulation, system memory, real time clock
  - *Communications board can vary as needed between sensor node and hub*
    - Wireless communications, USB or Ethernet controller, or UART pass-though
  - *Analog board is unique to the sensor node*
    - Analog board can be used to meet requirements for a wide range of transducer elements
    - Provides transducer excitation and signal conditioning
    - Direct access to all 8 microcontroller ADC channels,
    - Could incorporate multiplexers if additional transducers are required









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Corrosion Sensing and Monitoring

- Existing corrosion sensing technologies can be divided into three categories:
  - *Instantaneous corrosion rate measurements*
  - *Cumulative corrosion and material loss measurements*
  - *Environmental measurements*
- A suite of sensors offers the most robust measurements for building diagnostic algorithms and automating sensor validation routines
  - *Corrosion damage can be measured using surrogate samples, or inferred with environmental data*

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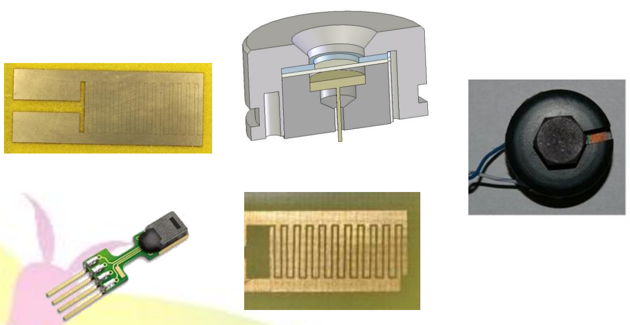
Sensor Development

- Miniature, light weight sensor suite can be used to measure corrosive severity of operational environments
- The sensor suite permits instrumentation of critical components, inaccessible areas, and “corrosion hotspots”
- Monitors multiple environmental parameters and corrosivity
  - *i_{corr}, E_{ocp}, ER, Inductance, RH, T_{air}, T_{surf}, TOW, $[Cl^-]$*
- Supports data fusion for improved state awareness and reduced uncertainty in estimating corrosion damage

Individual Sensing Elements



Sensor Suite

Sensor Node

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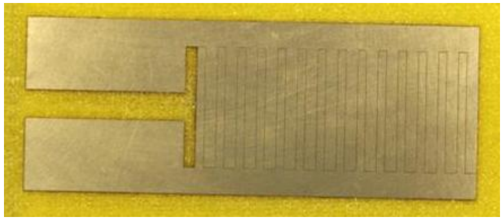
Instantaneous Measurements

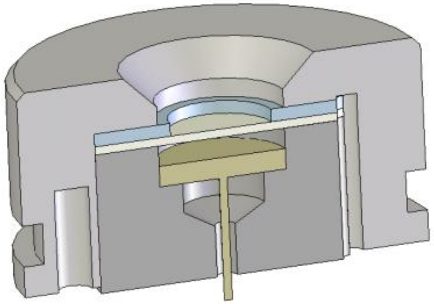
- Instantaneous measurements are used to characterize corrosivity at any given time
  - *A measure of cumulative damage can be obtained by integrating periodic corrosion rate measurements*

Sensor	Comments
Corrosion rate	Low power and low frequency excitations. Provides a measurement of R_p for calculating i_{corr}
Corrosion potential	Passive device. Requires high impedance input circuitry. Electrochemical measurement of E_{ocp}

AA7075-T6 interdigitated electrode



Ag/AgCl electrode



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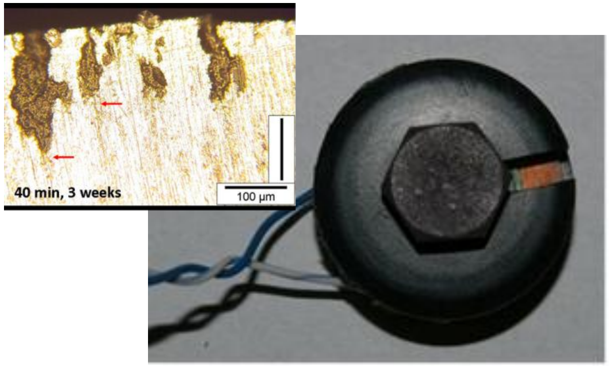
Cumulative Corrosion Sensors

- Cumulative corrosion sensors measure the total damage to a sensing element
  - *The total amount of damage can be determined at any time*
  - *Corrosion rate from the change in state for a given time interval*

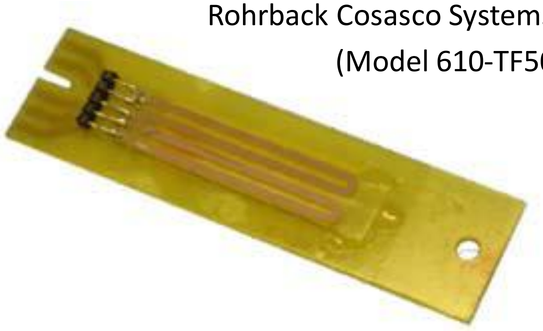
Sensor	Comments
Inductive/Eddy Current Sensor	Requires low power AC excitation. Inductive coupling between sensor and surrogate sample provides measure of material loss. Sensor can be used for localized corrosion of an alloy.
Electrical Resistance Probe	Low power Wheatstone bridge measurement technique. Resistive changes dependent on material loss. Typically a copper sensor for generalized corrosion.

Inductance sensor



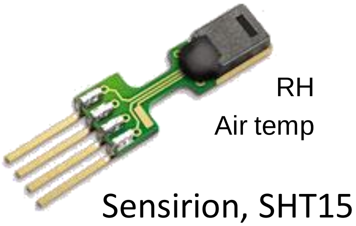
ER probe

Rohrback Cosasco Systems
(Model 610-TF50)



Environmental Sensors

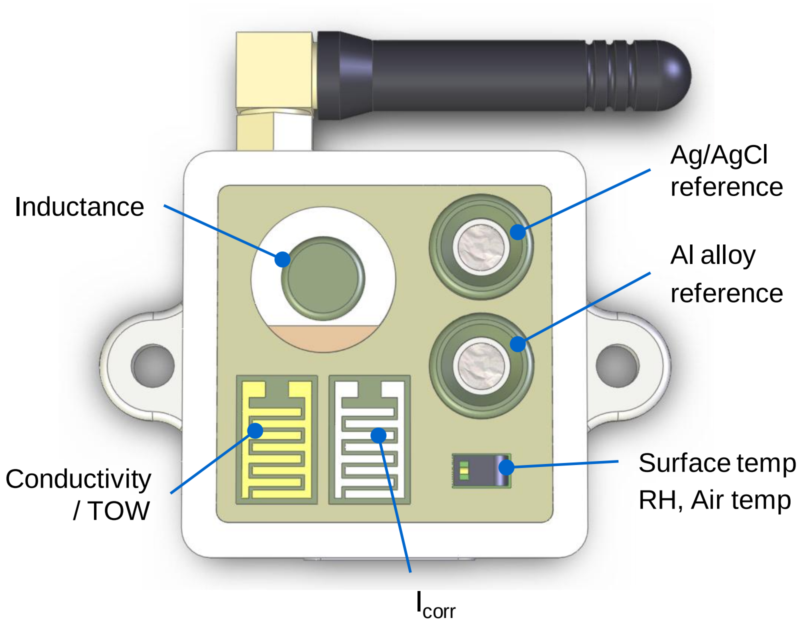
- Environmental sensors are used to measure corrosivity
  - *Atmospheric conditions or microclimates within a structure*



Sensirion, SHT15

Au/Au interdigitated

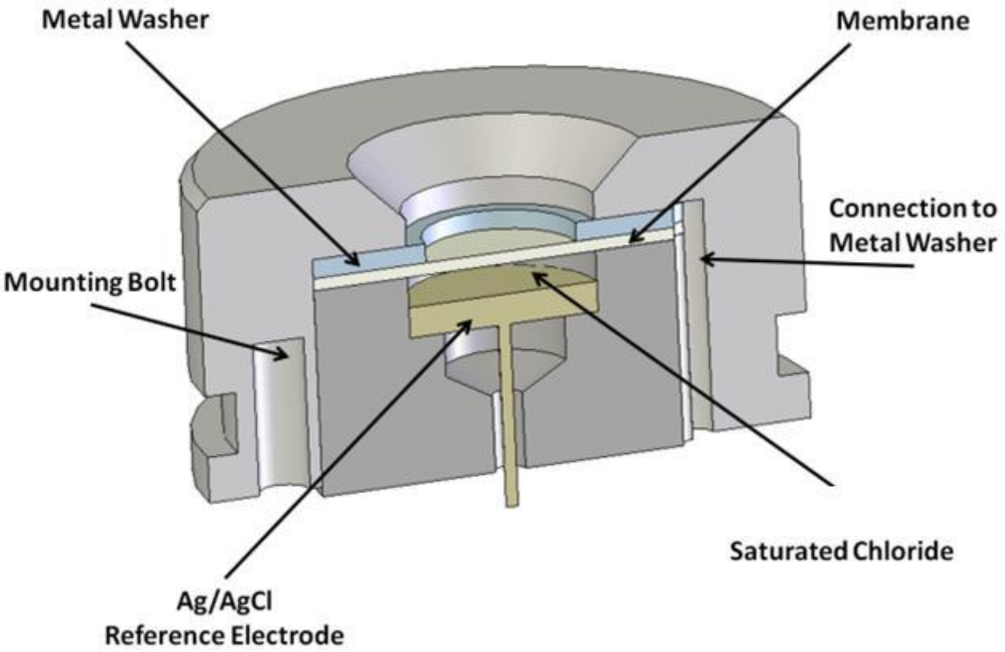
Sensor Technology	Specifications & Comments
Time of Wetness (TOW) / Surface conductivity	Gold-gold interdigitated electrode design. Requires low power, low voltage AC excitation source.
Chloride Sensor	Passive device. Requires high impedance input circuitry.
Relative Humidity / Air Temperature	Miniature, digital module +/-2.0% RH accuracy, +/-0.3% Temp accuracy. Average power consumption of 150µW.
Surface Temperature	Platinum RTD with accuracies to +/-0.15°C @ 0° (Class A RTD). Sensors can be driven with low power constant current circuitry.



Reference Electrode

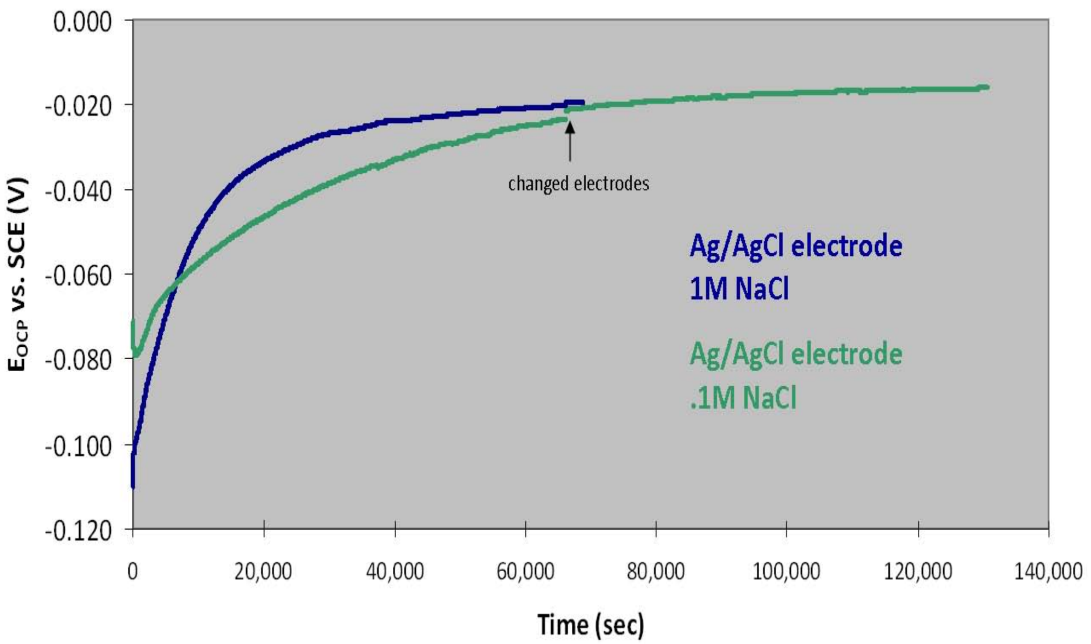
- Reference electrodes are used to measure the corrosion potential (E_{ocp}) for a given alloy and environment
  - *For a given alloy, E_{ocp} can be used to predict pitting or uniform corrosion*
  - *AA2024-T3 or AA7075-T6 working electrode*
- Reference electrode can also be used to measure chloride concentration (Nernst Equation)
  - *Pure silver working electrode for measuring [Cl^-]*

$$E = E^o - \frac{RT}{F} \ln a_{cl^-}$$



Reference Electrode

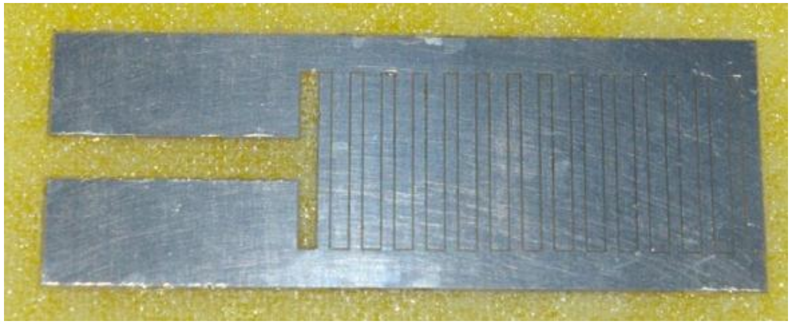
- Reference electrode testing for stability of potential measurements
  - *0.01, 0.1, 0.5, and 1. M NaCl solutions in 90% RH*
  - *Immersions tests at 1.0 and 0.1 M NaCl*
  - *long term potential is unaffected by chloride concentration*



Interdigitated Electrodes

- Interdigitated electrodes can be used to measure polarization resistance (R_p) and solution resistance (R_s)
  - *Corrosion rate (i_{corr}) can be determined from R_p*
  - *R_s is dependent on salt concentration*
  - *R_s can be used to measure time of wetness*

Interdigitated electrode
(AA7075 & AA2024)

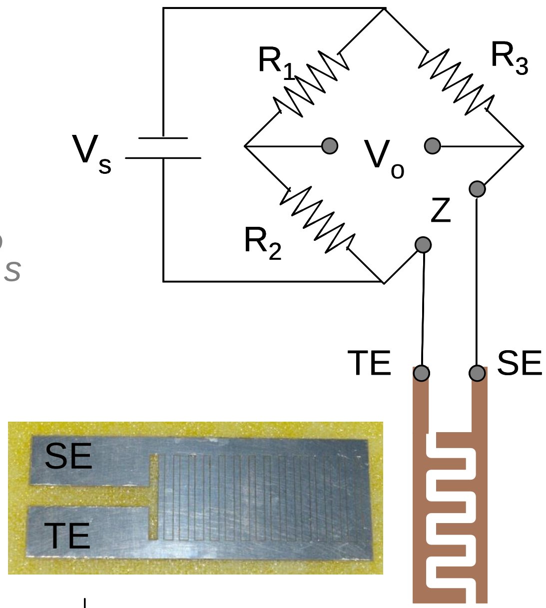


Luna interdigitated electrode
(gold)

Interdigitated Electrodes

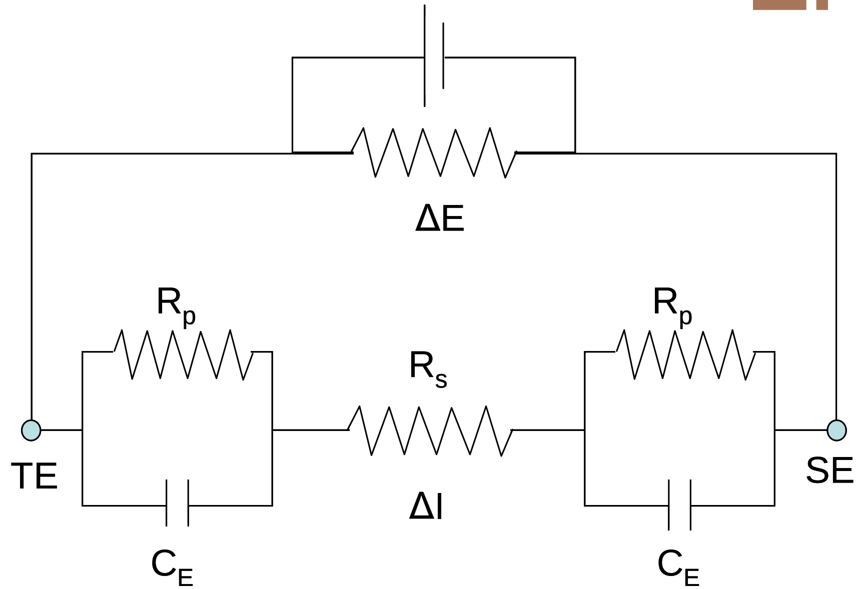
- Polarization resistance
  - *Impedance analysis used to determine R_p*
  - *Two electrode measurement*
  - *Low frequency excitation to measure $2R_p + R_s$*
  - *High frequency measurement for R_s*

$$R_p = \left(\frac{\Delta E}{\Delta i}\right)_{\Delta E \to 0} = \frac{b_a b_c}{2.3(b_a + b_c) i_{corr}}$$, or $$i_{corr} = \frac{B}{R_p}$$



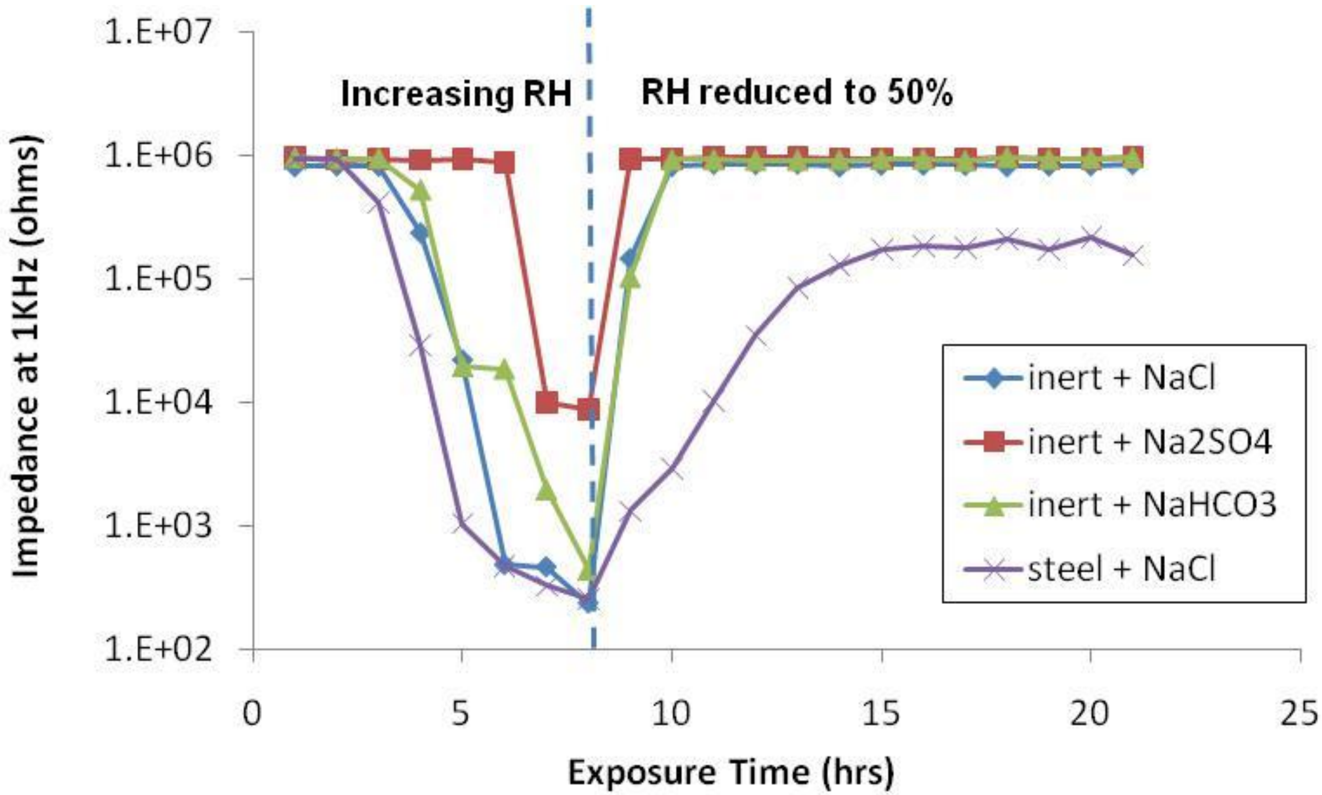
$$Z_{\omega \to 0} = 2R_p + R_s$$, and $$Z_{\omega \to \infty} = R_s$$

$$R_p = \frac{Z_{\omega \to 0} - R_s}{2}$$



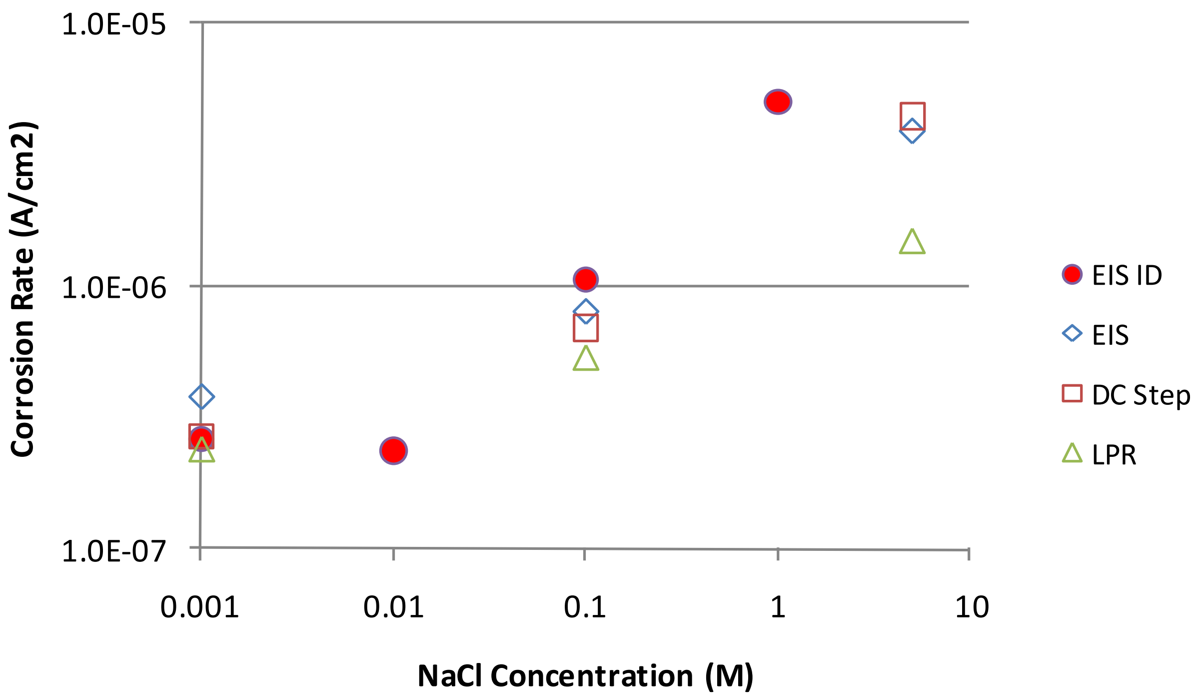
Interdigitated Electrodes - TOW

- Impedance magnitude for Au/Au sensor excited at 1 kHz indicates TOW and deliquescence point of surface
- Relationship of RH to corrosivity is dependent on deliquescence of salt deposits and corrosion products



Interdigitated Electrodes - i_{corr}

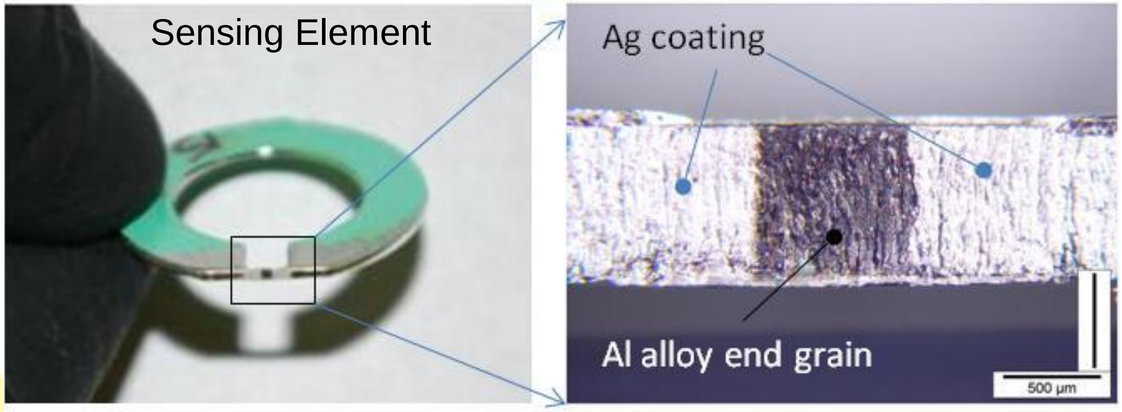
- Copper corrosion rates were measured by a number of techniques over a range of salt concentrations
- Flat copper plate electrodes were evaluated LPR, EIS and DC step methods
- Interdigitated electrodes were tested using low frequency (0.01 Hz) 5 mV excitation
- There is reasonable agreement between EIS with the interdigitated electrode and other measurement methods

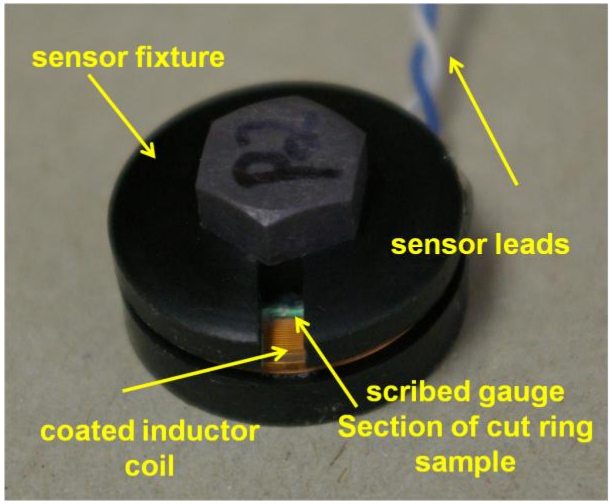


Inductive Corrosivity Sensor

- Inductive corrosivity sensor measures cumulative corrosion damage
  - *Sensitive to localized corrosion*
  - *Coating system breakdown*
- Sensor is composed of an induction coil and sensing element (AA2024-T3 or AA7075-T6)
  - *Sensing element is fabricated so gage section has exposed end grains*

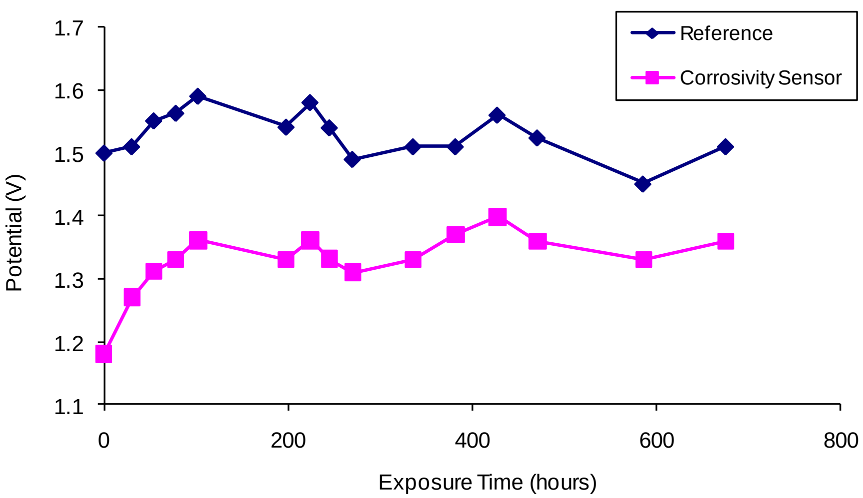
Assembled sensor

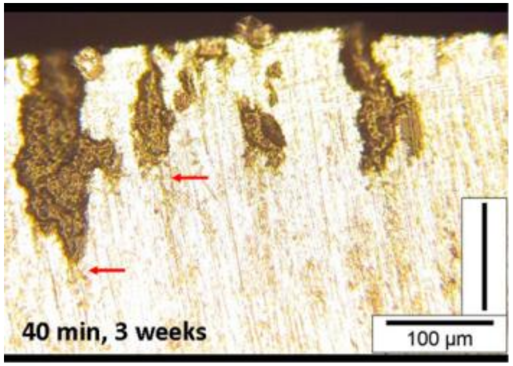




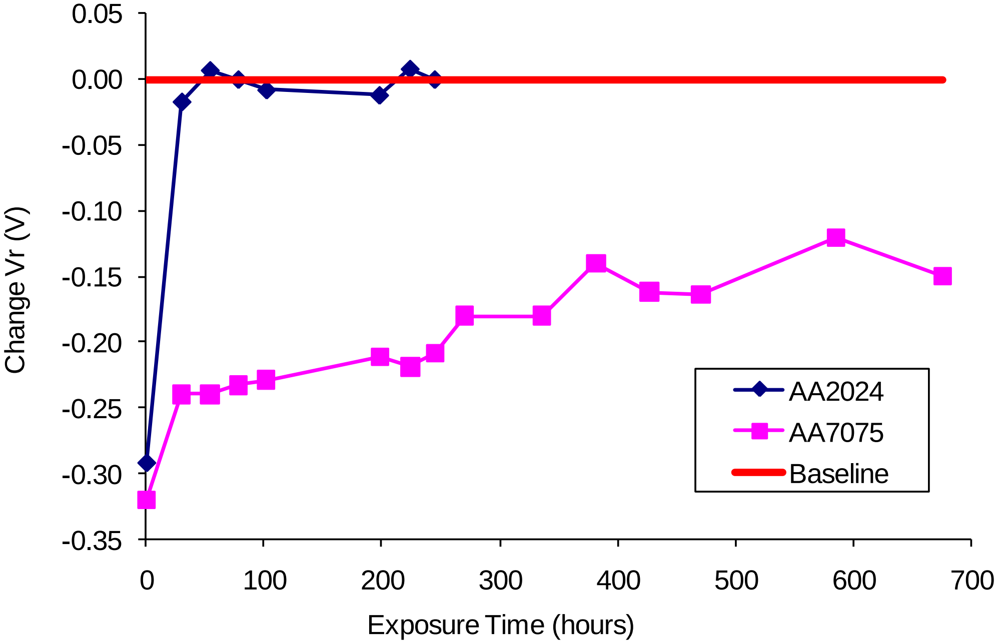
Inductive Sensor

- Inductive sensor can detect changes in gage section geometry due to corrosion
  - *AC current excitation*
  - *As corrosion occurs, induced EMF into sample decreases*
  - *Need to relate output to corrosion damage*



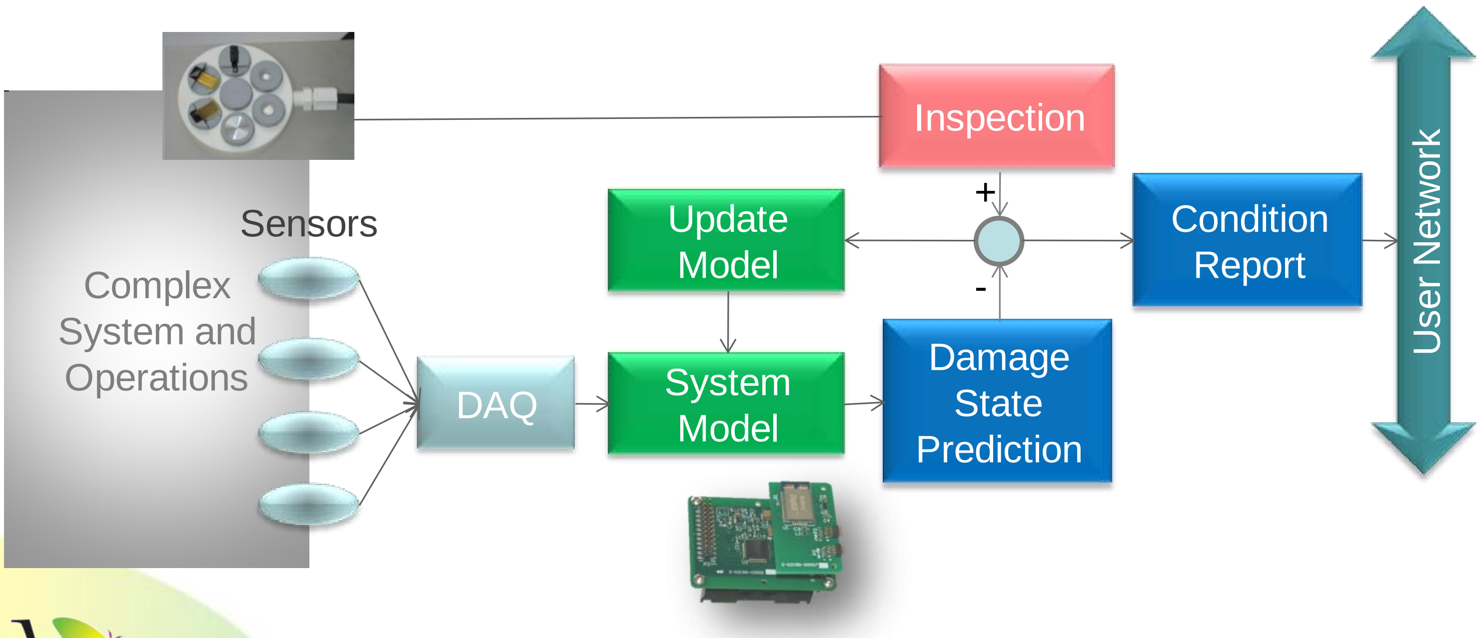


Gage cross-section



Algorithm Development

- The system is designed to support data processing at the sensor node and hub
  - *Embedded diagnostic and prognostic routines including automated sensor validation*
  - *Data reduction decreases the overall data volume, thus requiring fewer data transmissions*
  - *Reduction in communications lowers system power consumption*
- Designed experiments and accelerated corrosion tests will be performed to establish diagnostic algorithms



Sensor Node

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Sensor Hub